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GALAXY FORMATION, NON BARYONIC MATTER AND COSMIC STRINGS

David N. Schramm

Nicola Vittorio

University of Chicago

and Fermilab

ABSTRACT

A review of the current problems in galaxy formation with dark matter is made. Most of the difficulties may be eliminated if fluctuations can be generated in the early universe that are not carried by the matter until matter domination, then baryons alone can form galaxies and clusters. Such fluctuations can be produced by Grand Unified phase transitions such as the breaking of 0(32) or E(8) x E(8) which produce cosmic strings. However, to be consistent with the critical density universe required by Inflation one still requires an additional non-baryonic component.

A major problem in cosmology today is the formation of galaxies and clusters in the universe. The problem has become quite focused as cosmologists have accepted grand unified theories, GUTs, for the production of baryons in the universe[1], and inflation yielding a flat universe, i.e. $\Omega_o=1$, if the cosmological constant is assured to be equal to zero. (Ω is a measure of the present cosmological density in units of the critical density $\rho_{crit}=\frac{3H^2_0}{8\pi G}$. Such models suggest adiabatic primordial density fluctuations[2] with a scale-invariant power spectrum $\delta_k^2 \propto Ak$. The amplitude A which depends on the individual GUT model can be constrained by observations. A lower bound comes from the requirement that A is large enough to produce the present degree of clustering (assuming that observed galaxies are a fair tracer of the overall mass distribution). Since an adiabatic density fluctuation necessarily induces fluctuations in the cosmic microwave background (CMB) temperature, at the epoch of the matter radiation decoupling, at a redshift z $\sim$ 1000, an upper bound is found in order to be consistent with the observed CMB smoothness.

The most recent and sensitive upper limit[3] on the CMB anisotropy shows that $\frac{\delta T}{T} \leq 2.5\times 10^{-4}$, on an angular scale of 4′.5, $\frac{\delta T}{T} < 4\times 10^{-6}$ on an angular scale of 6°, quadrapole anisotropy $Q < 7\times 10^{-6}$. It is known that $\frac{\delta\rho}{\rho}$ grows linearly with the expansion of the universe until $\frac{\delta\rho}{\rho} \sim 1$ is achieved (for an open universe, $\Omega_0 < 1$, growth stops effectively at a redshift $z \sim 1/\Omega_0$. Using the above assumptions, detailed calculations of the small scale CMB anisotropy have ruled out pure baryonic universes for any choice of an initial adiabatic scale-free random phase power spectrum[4]. Then, attention has been focused on cosmologies dominated by non-collisional relics of the early universe. Popular options included massive neutrinos, photinos, gravitinos, axions, planetary mass black holes, quark nuggets, etc. The only distinctive feature among these different candidates, as far as galaxy formation is concerned, is the velocity dispersion: one refers to cold matter when the rms particle velocity is vanishing small, relative to the Hubble flow, and to hot matter when the opposite holds up to some redshift, comparable to or smaller than the redshift of matter radiation equality[5].

In the hot matter case (the leading candidate being neutrinos), with $m_\nu \sim (10-100)eV$, non-collisional damping due to free-streaming erases all the information on galactic scales, and a top-down scenario is expected in which galaxies form through fragmentation of larger systems. At least three points seem to suggest that this scenario is in difficulty. Numerical simulations of the non-linear evolution of structure in a neutrino dominated universe show that galaxy formation occurs too late ($z < 1$) to be consistent with the observed high redshift quasars[6]. Moreover, both the large scale peculiar velocity[7] and the dipole anisotropy[8] exceed the observed values, if one forces galaxy formation times to be consistent with the existence of quasars at a redshift ~ 3 and with a reasonable age for the universe.

In the cold dark matter scenario, non-collisional damping phenomena are absent and density fluctuations are present down to subgalactic scales. A bottom-up scenario is expected in which small scale structure forms first to cluster hierarchically on bigger and bigger scales. The advantage is, with respect to the hot case, that high redshift quasars are naturally expected. However,

the cold matter scenario also seems to have its own difficulties. On one hand, calculations[9] of the CMB fine scale anisotropy in the cold dark matter dominated case require $\Omega > 0.4$ if the universe is older than 13×10^9 years as required by globular cluster age observations[10]. On the other hand, non-linear cold matter calculations are able to fit obsevations of the two-point galaxy correlation function by requiring $\Omega_c = 0.2$, but even then, they only marginally fit pairwise galaxy velocity dispersion[11]. The problems with cold matter become severe if we require $\Omega_c = 1$ as implied by inflation and necessitated if we are not to live at a special comological epoch. Cold matter clumps on small scales but Ω implied by small scale observations is significantly less than unity.[12,13]

Attempts at remedying the situation with a hybrid mixture of hot and cold matter fail[14] due to the hot matter's damping the low mass scales and thus preventing the cold particles from rapidly clustering. It is possible to create a solution where non-baryonic particles decay to hot ones,[15] but the particle physics of such a solution is very ad hoc, requiring much fine tuning to achieve agreement with observations.

It is also possible to save the cold scenario if the additional assumption is made that light is not an unbiased tracer of mass and that there are many clumps of cold matter and baryons which are not shining, thus enabling Ω to be unity. It has been shown[17] that if galaxies only form in the higher peaks of the fluctuation density field, they are more correlated than the overall mass distribution and the non-linear simulations can be reconciled with the observations[11]. There are some potential difficulties. Such a solution implies a very smooth fluctuation density field which yields a low large scale peculiar velocity field. The current data are still very uncertain, but if velocities as high as $350 kms^{-1}$ are confirmed, a biased dark matter scenario would be in difficulty.[8]. Moreover, in the bias model, the two-point galaxy correlation function $\xi_{gg}(r)$ and the two-point cluster correlation function, $\xi_{cc}(r)$ are predicted to be proportional[18]. Current observations[19] show that ξ_{cc} is positive out to $r \gtrsim 100 Mpc$ while there is evidence that $\xi_{gg} \leq 0$ on scales of $\sim 20 Mpc$. In fact, any scale invariant power spectrum must yield a negative ξ_{gg} by a few tens of Mpc. Finally, it should also be mentioned that a physical mechanism to produce biasing must be able anisotropes in the CMB, present limits do not rule out the strings needed for galaxy formation.

It is also interesting that strings yield non-random phase fluctuations,[31] thus providing a way to understand very large-scale non-linear fluctuations[31,32] in today's universe, whether super-clusters or voids. Although present observations do not require non-random phases[33], they should yield a fractal of dimension D $\sim$ 1, which corresponds well with the galaxy-galaxy and cluster-cluster correlation functions, and fits well the requirements for scale-free clumping.[34] It is interesting that the two current best candidates for a super-unified Theory of Everything(T.O.E.), O(32) and E(8) x E(8) both break at the GUT epoch into cosmic strings.[35]

Unfortunately, neither strings nor cold dark matter by themselves address the large scale dark matter problem of inflation implying $\Omega_0=1$, while clustered matter[5,11,12,13] implies $\Omega_0<0.2$. This problem is solved extraordinarily well by hot matter, since the natural minimum collapse scale,[36]

$$M_{Jmax} \sim 3\times 10^{18}/m_\nu^2(eV),$$

gives a good fit, for 10 to 30 eV neutrinos, to the large scale structure of the universe. Although this was an initial support for hot matter, the neutrino and other hot candidates subsequently fell into the difficulties mentioned earlier.

A solution which can save the hot scenario (which has always been nice for obtaining $\Omega_0=1$) and retain dark baryonic matter as the solution to the dark halos is to have a hybrid of strings, hot matter and the baryons which are required by nucleosynthesis anyway. In such a hybrid, the hot matter will begin to fall into the fluctuations created by the strings once the hot matter dominates over radiation. Again, string fluctuations will exist isothermally for all scales greater than galaxy size; however, phase space constraints[37] plus the neutrino Jeans mass will prevent large numbers of neutrinos from clustering on small scales, thus keeping $\Omega_{clustered}$ low. As before, baryons will fall into preexisting fluctuations once they decouple from the radiation, so no conflict with $\frac{\delta T}{T}$ need occur.

It is interesting that a major difference between the different solutions to the $\Omega_0=1$ problem is where the dark baryons go. In the bias models, the dark baryons are not associated with galaxies or clusters, whereas in the hot plus strings scenario, the dark baryons form the halos of galaxies. Since baryons are, in principle, observable, this must lead to observational tests.

In summary, a process such as GUT-strings coming out of the early universe, which yields gravitational potential fluctuations that are only coupled by gravity to matter, is exceedingly useful for galaxy formation, and can solve many difficult aspects of the cosmological dark matter problems.

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identified. Up to now, the criteria for clumps of matter shining or not shining is ad hoc, however, attempts at quantifying the situation are being developed[20]. (Hot matter might also be saved with light's not tracing the mass, but with the assumption that higher density clumps don't shine in any EM-band, while cold requires the low density clumps not to shine. However, the original idea was to have a biased galaxy formation as a consequence of a statistical effect due to the presence of small scale fluctuations on galactic scale, superimposed on large scale fluctuations. In the massive neutrino case, this seems to be more artificial.)

In discussing the unseen matter, it must be remembered that Big-Bang nucleosynthesis[21] argues that the fraction of the critical density in baryons, Ω_b, cannot exceed 0.15, and when combined with age arguement, must[13] exceed 0.03, whereas the light emitting regions have $\Omega<0.01$. Therefore, some of the baryons must be dark. Since the dynamics of galaxies[22] in binaries and small groups imply $\Omega\sim0.1$, and even the dynamics of the largest clusters don't imply an Ω significantly greater, it is natural to associate the dark baryons with the dynamical halos,[23] although this is by no means mandatory. (Dark baryons could[24] be in the form of black holes, or very low mass, low-luminosity stars or "Jupiters", if the initial mass function is strongly peaked at the low end.) In other words, a pure baryonic universe with $\Omega\sim0.1$ is perfectly consistent with the observations[23]. It is only the theoretical arguments favouring $\Omega=1$ and the need to rapidly form galaxies that cause problems.

If primordial fluctuations could be generated which are not carried by the matter, but remain pristine until matter begins to fall into them near the time of recombination, then the matter and radiation can be kept smooth (small $\frac{\delta T}{T}$) until recombination, without any damping due to free-streaming or radiation viscosity. After baryonic matter decouples from radiation, it can fall into the pre-existing potential wells. Thus, as in the old isothermal view, limits on $\frac{\delta T}{T}$ imply weaker constraints on the amplitude of the primordial fluctuation spectrum. Wilson[4] demonstrated that the constant power fluctuation spectrum (n=1) for initially isothermal perturbations, only yield $\frac{\delta T}{T}\sim2\times10^{-6}$ while still having $\frac{\delta\rho}{\rho}\sim10^{-3}$ at radiation decoupling, so that $\frac{\delta\rho}{\rho}$ can exceed unity today.

Previously, such a possibility of a fluctuation being unrelated to matter was thought impossible given the need for GUT's to generate baryons, but GUT phase transitions which lead to cosmic strings[25] can give just such a situation.[26]

In such a situation, the GUT phase breaks via filaments rather than bubbles, analogous to how some condensed matter phase transitions produce needles rather than grains. Large classes of GUT models can break in this manner. (In order to be consistent with our universe, it would also be nice if such models also yielded their monopoles at a higher mass scale, so they could be inflated away while producing the strings at the end of the transition.)

Strings left on length scales larger than the horizon survive. As they cross or fragment to produce loops, gravitating seeds are formed which become the fluctuations that matter can fall upon once matter dominates the energy density of the universe, and, in the case of baryons, once the matter decouples from the radiation.

Vilenkin[25] and Turock[27] have shown that the fluctuation spectrum produced by such strings is, like in other GUT cases, just a Harrison-Zeldovich type with constant power on all scales $> M_{galaxy}$. (Scales smaller than this are radiated away by the gravitational radiation from the small loops of string.)

The energy density left in strings varies with the model. To avoid the problems of string dominated universes,[28] it is only necessary that the energy density left in strings, ρ_s, be $<<\rho_{matter}$. In particular, from limits on $\frac{\delta T}{T}$, we obtain $\frac{\delta\rho}{\rho}\sim\frac{\rho_s}{\rho_{matter}}<10^{-5}$. Hogan and Rees[29] have pointed out that strings of this magnitude will gravitationally radiate, and that such radiation will eventually modulate the gravitational radiation from the gravitational decay of the binary pulsar's orbit. Thus, eventually one might hope to see evidence for the existence of such strings from the timing of the binary pulsar. The current measurements are not yet sufficiently accurate. Kaiser and Stebbins[30] have shown that in addition to the CMB anisotropes produced by fluctuations at the last scattering surface, strings can directly produce small but potentially obsev-

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